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Gravitational Waves from Stellar Collapse

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Abstract. Stellar core-collapse plays an important role in nearly all facets of astronomy: cosmology (as standard candles), formation of compact objects, nucleosynthesis and energy deposition in galaxies. In addition, they release energy in powerful explosions of light over a range of energies, neutrinos, and the subject of this meeting, gravitational waves. Because of this broad range of importance, astronomers have discovered a number of constraints which can be used to help us understand the importance of stellar core-collapse as gravitational wave sources.

INTRODUCTION

The increasing reality of gravitational wave (GW) detectors sufficiently sensitive to observe a host of astrophysical GW sources has led to a flurry of activity among astrophysicists to estimate these sources. One of the most studied class of GW sources involves the collapse of massive stars to form compact remnants (either neutron stars or black holes). This class includes a variety of astrophysical objects with a range of masses from the collapse of a Chandrasekhar-massed white dwarf to the collapse of very massive stars with masses in excess of $250\,\mathrm{M}_{\odot}$.

Although there is little doubt that stellar collapse produce gravitational waves, it is difficult to accurately estimate the characteristics of the signal produced. These difficulties arise not just from uncertainties in the collapse itself, but also in the evolution of the *progenitors* of these objects. Fortunately, observational evidence of stellar collapse is not limited to gravitational waves. Stellar collapses produce compact remnants, neutron rich isotopes, neutrino and photon outbursts. All of these “observables” can be used to place some constraints on these events. By tapping into this store of astrophysical knowledge, we can get some understanding of GW emission from stellar collapse.

Here we review the current understanding of 3 distinct collapse events: the collapse of an accreting white dwarf pushed beyond the Chandrasekhar limit (Accretion Induced Collapse), the standard core-collapse supernova model, and the collapse of very massive stars ($\sim$250-500$\mathrm{M}_{\odot}$). The rate that each of these collapse events occurs is known to some degree (although except for core-collapse supernovae, we can only place upper limits on the rate). Also, at varying levels of accuracy, we know the photon and neutrino outbursts that accompany the collapse (and the GW emission). Predicting the GWs themselves is much more difficult and a complete discussion of the possibilities is beyond the scope of this paper. However, for many instabilities which drive the emission of GWs, the strength of the gravitational wave emission depends upon the mass and angular momentum in the emitting region. Here we will review the constraints astronomers can place on the collapse rates, neutrino and photon outbursts, and the mass and angular momentum distributions that arise from stellar collapse.

ACCRETION INDUCED COLLAPSE

When a white dwarf's mass exceeds the Chandrasekhar limit, it begins to collapse. As it contracts, its temperature increases adiabatically. Neutrino cooling (via Urca processes) limits the rise in temperature. If neutrino cooling does not reduce the adiabatic heating significantly, the collapsing white dwarf will reach temperatures hot enough to ignite nuclear burning. The entire white dwarf explodes in a thermonuclear explosion known as a Type Ia supernova. If, on the other hand, cooling initially prevents nuclear ignition, the white dwarf will collapse more and more quickly as electrons capture onto protons and the white dwarf will ultimately form a neutron star.

This "Accretion-Induced Collapse" (AIC) of a white dwarf is very similar to core-collapse supernovae. The collapse of white dwarfs has been studied in some detail over the past few decades (Hillebrandt, Nomoto, & Wolff 1984, Woosley & Baron 1992, Fryer et al. 1998) and we have some understanding of the collapse process and the resultant explosion. Since the white dwarf is pushed over the Chandrasekhar mass limit through disk accretion, it is likely that the collapsing white dwarfs will contain a considerable amount of rotation, allowing the possibility of a variety of instabilities and the emission of GWs. For this paper, we rely upon the rotating core collapse models from Fryer et al. (1998).

Formation Rate

Calculating the formation rate of AICs from first principles is fraught with a number of difficulties from understanding binary star evolution to uncertainties in the accretion process itself. We have already mentioned one such uncertainty: Does the star ignite in a thermonuclear explosion or collapse to form an AIC? However, we currently don't even understand what conditions are necessary for a white dwarf to actually accrete matter instead of losing it via a series of nova explosions. To calculate the rate of AICs, we must then rely upon indirect methods.

First, the thermonuclear explosion of a Chandrasekhar-massed white dwarf seems to match supernova observations well (see Pinto & Eastman 2000 for example) and it is almost certainly the mechanism which produces Type Ia supernovae. Hence, we know that, roughly every few hundred years in the Galaxy, a white dwarf does accrete enough mass to exceed the Chandrasekhar limit (Cappellaro et al. 2000). Some fraction of these white dwarfs will collapse to form a neutron star. Which fate befalls the white dwarf depends sensitively upon the initial mass of the white dwarf, its chemical composition, and the rate at which it accretes matter (see Nomoto & Kondo 1991 for review), making an accurate estimate nearly impossible.

However, by modeling the collapse, we can place constraints on the AIC rate. During the collapse, the white dwarf ejects the outer $\sim$0.1 $M_{\odot}$ of its envelope, some of which became very neutron rich due to electron capture. As this material is ejected, it forms some extremely rare, neutron-rich isotopes, which "pollutes" the Galaxy. By measuring the total amount of these isotopes in the Galaxy, and assuming these isotopes are formed solely in AICs, we can place an upper limit on the rate of AICs in the Galaxy at about 10^{-5} per year (Fryer et al. 1998).

Neutrino and Photon Outbursts

During the collapse, electrons capture onto protons ($e^- + p \rightarrow n + \nu_{\rm e}$) and the collapsing object produces a burst of electron neutrinos. As the core collapses, it gradually becomes optically thick to neutrinos and the neutrino luminosity is cut off. Slowly, neutrinos leak out of the core, but as the core temperature increases, pair annihilation produces neutrinos of all flavors and these neutrinos cool the proto-neutron star (just as the electron neutrinos reduce the electron fraction) and allow the core to eventually become a young neutron star.

At the same time as this neutron burst, the matter in the core collapses down to nuclear densities where nuclear forces and neutron degeneracy pressure abruptly halt the infall and the core bounces. The inner core has become a "proto-neutron star". The bounce causes the outer layers of the white dwarf to expand out of the potential well of the proto-neutron star. Neutrinos leaking out of the core heat the outer $\sim$0.1-0.15 $M_{\odot}$ of the white dwarf and eject it in a mini-supernova explosion. As the ^{56}Ni in this ejecta decays, it powers a weak supernova outburst similar to Type Ia supernovae, but $\sim$10 times dimmer. To date, there are no convincing observations of AIC outbursts. Remember, however, that the rate of AICs is less than 1% of the Type Ia supernovae rate and it is not surprising that we have not yet observed an AIC.

Gravitational Wave Emission

Typically, estimates of the GW emission from core-collapse concentrate on the initial collapse and bounce phase of the star. It is at this early stage that the core is moving quickly and a rapidly varying quadrapole moment can be produced *if* some instability occurs. The strength of the gravitational waves depends on the amount of mass in the core and the rotation rate (which determines the likelihood of an instability to develop).

First, lets discuss the density distribution shortly after bounce. Because the neutrinos are trapped in the core, both the temperature and the electron fraction of the proto-neutron star remain high for nearly 10 s. Hence, the proto-neutron star remains extended during this time. To estimate gravitational waves, we must use the density distributions of these extended neutron stars. The density profile of an AIC 0.18s after bounce is given in figure 1.

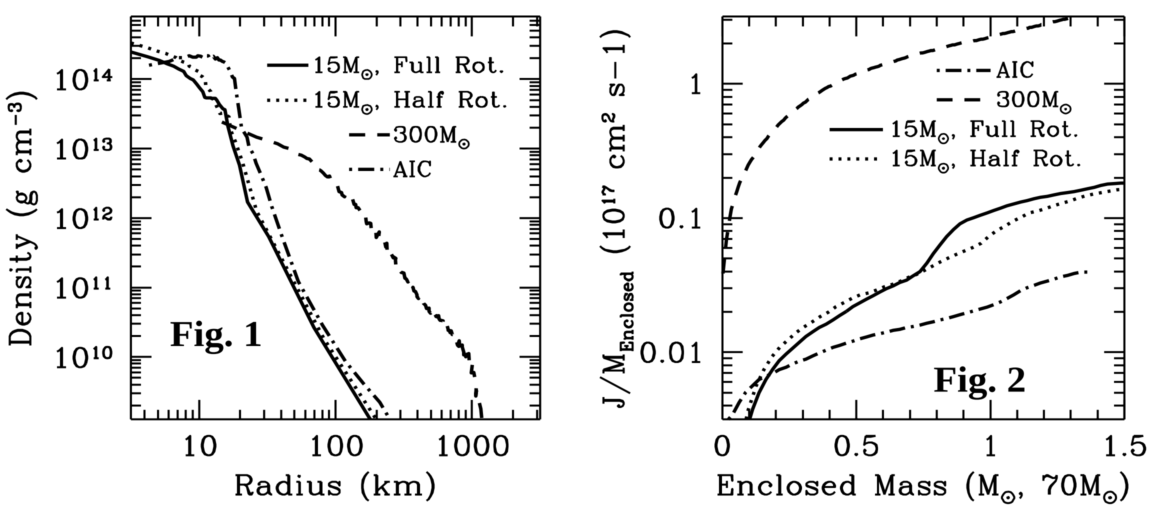

FIGURE 1. Density (Fig. 1), Angular Momentum (Fig. 2) versus radius for collapsing stars: AIC-0.18 s after collapse, rotating core-collapse (full rotation)-1.6 s after bounce, core-collapse (half rotation)-1.4 s after bounce, 300 $M_\odot$ direct collapse-1.9 s after collapse. For the core-collapse simulations, the slower rotator is more dense. Although the maximum density of the 300 $M_\odot$ direct collapse is much lower than other core-collapse, its mass out to 1000 km is 50 times that of the other collapsed objects. Note in Fig. 2 that the 300 $M_\odot$ has, by far, the highest angular momentum.

Even more important is the distribution of angular momentum in the proto-neutron star. The moment of inertia of a typical white dwarf is small ($IM^{-1}R^{-2} < 0.1$) and the accretion of only a few tenths of a solar mass through an accretion disk can cause the the white dwarf to spin up nearly to break-up. For a 10,000 km, Chandrasekhar-massed white dwarf, this corresponds to a spin period of 14.5 s (for a 2,500 km white dwarf, the corresponding break-up spin period is 1.8 s). Such high spin rates are not seen in white dwarfs. Indeed the fastest spinning white dwarfs observed thus far have periods in excess of 100 s. Fryer et al. (1998) modeled AICs assuming a maximum total angular momentum of $10^{49}\,\mathrm{g\,cm^2\,s^{-1}}$. This corresponds to a 100 s spin period for a 10,000 km white dwarf or a 12.5 s period for a 2,500 km white dwarf. 0.18 s after bounce, half of the angular momentum is in the 0.8 $M_\odot$ proto-neutron star (Fig. 2).

Let's discuss two types of instabilities which might drive the generation of gravitational waves: bar modes and rossby modes. Bar mode instabilities occur in objects whose rotational energy exceeds some fraction of its potential energy. This fraction is generally written as $\beta \equiv T/|W|$. The standard lore is that an object is unstable on a secular time scale if $\beta \gtrsim 0.14$ and it is dynamically unstable if $\beta \gtrsim 0.27$. Unfortunately, for AICs, our $J=10^{49}\,\mathrm{g\,cm^2\,s^{-1}}$ is not unstable 0.18 s after bounce (Fig. 3). As the proto-neutron star cools, β may increase, but it is unlikely that such instabilities will affect much of the mass in the nascent neutron star and it is unlikely that they will produce strong gravitational waves. One might imagine a faster rotating white dwarf, but it is not clear that nature produces them and the one should not rely upon bar-modes producing any detectable GW signal.

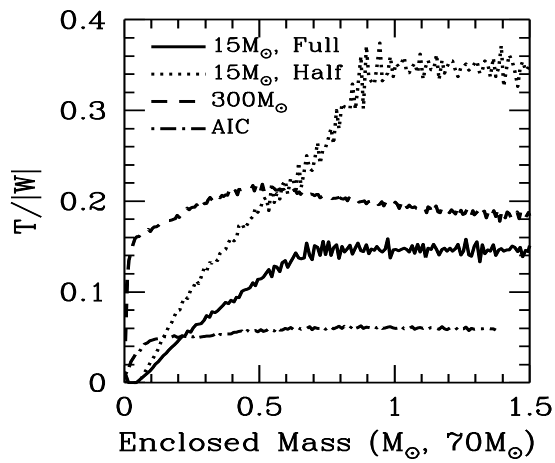

FIGURE 2. Rotational energy divided by gravitational energy ($T/|W|$) versus mass for the 4 collapse progenitors from Figs. 1,2. For the core-collapse stars, $T/|W|$ is actually higher for the star initially spinning at half the rotation rate. This is because it is more compact.

However, as the neutron star cools and contracts, the angular momentum in this object will produce a sub-ms neutron star. If r-modes exist, AICs will produce a signal as strong as any young neutron star formation scenario. However, given that the rate is 1000 times lower than standard core-collapse supernovae, it appears that core-collapse supernovae, not AICs are a better GW source.

CORE-COLLAPSE SUPERNOVAE

Stars more massive than $\sim$8 $M_\odot$also end their lives in a core-collapse. During their lives, successive stages of nuclear burning build up a massive iron core in the stellar center. This iron core is supported by electron degeneracy and thermal pressures. When the density and temperature in the core become so high that a) iron is dissociated into alpha particles and b) electron capture occurs, the support pressure is suddenly removed and the core collapses. As it collapses, the core density and temperature increases, causing more iron dissociation and electron capture which leads to a runaway infall of the core. Just as with AICs, the core collapses until it reaches nuclear densities where nuclear forces and neutron degeneracy pressure abruptly halt the collapse.

Astronomers have long understood that the potential energy released as a star collapses down to a neutron star could power a supernova explosion (Baade & Zwicky 1934). However, it was not until 1966 that Colgate & White realized that neutrinos could be the medium which transported energy released during the collapse of the core into the outer layers of the star which could then explode and drive the supernova explosion. Since this time, astronomers have continued to refine the neutrino-driven model. Indeed, core-collapse supernovae are one of the few objects in astronomy that we do not invoke fudge factors to explain (albeit, this means that we do not yet match the observations well either).

The basic mechanism behind core-collapse supernovae has developed from 3 decades of study and is very similar to AICs. The main difference arises from the fact that the proto-neutron star must somehow eject $\gtrsim 10-15\,M_\odot$of material instead of $0.1\,M_\odot$in the case of AICs. After bounce, the inner portion of the star rains down upon the proto-neutron star, preventing a quick explosion that occurs in AICs. A convective layer above the proto-neutron star and below the pressure cap of the infalling material converts the heat deposited by neutrinos into kinetic energy, aiding the explosion. As we shall see, convection plays an important role in the supernova mechanism and in our understanding of rotating supernova collapse models.

A great deal of work has been devoted to studying gravitational waves from core-collapse. Generally, these simulations have simplified the physics in an effort to concentrate on the gravitational wave emission (see Rampp, Müller, & Ruffert 1998 for a review). The advantage of these simplifications is that some of the collapse simulations can actually be modeled in 3 dimensions. The disadvantage is that these simulations do not include enough physics to accurately model the structure of the star at collapse and this limits the reliability our models of the gravitational wave signals from core-collapse supernovae. In addition, until recently, no massive stellar models existed which evolved rotating stars to collapse, and the angular momentum profiles used in GW calculations of core-collapse have all been artificially put in (generally at spin rates which are much higher than we now expect in nature).

Formation Rate

The formation rate of core-collapse supernovae is fairly well known and lies somewhere between 1 per 50-140 years in the Galaxy (Cappellaro et al 1997). What we do not know is what fraction of these core-collapse supernovae (if any) are rotating rapidly enough to emit detectable amounts of gravitational waves. From measurements of young pulsars, we know that at least some neutron stars are born with periods faster than 20 ms. But whether or not any neutron stars are born with millisecond periods is hard to ascertain. The problem is that pulsars spin down as they emit radiation, but we don't know exactly how fast the spin-down occurs. The most recent analysis by Chernoff & Cordes (pvt. communication) found that they could fit the initial spin periods with a Gaussian distribution peaking at 7 ms with sub-ms pulsars lying beyond the 2-sigma tail. Does this mean that less than 10% of pulsars are born spinning with millisecond periods, or does it mean that many pulsars are born spinning rapidly and GW emission removes a considerable amount of their angular momentum? In addition, the analysis of Chernoff & Cordes is very sensitive to their choice of spin down rates and other uncertainties in their population study and such results should be taken with a great deal of caution.

Hence, although we know the rate of core-collapse supernovae to high accuracy (for astronomical standards), we do not know the rate of core-collapse supernovae which occur with sufficiently high spins to be interesting to observations of GWs. But perhaps, the explosion itself can provide us with clues.

Neutrino and Photon Outbursts

The neutrino burst from core-collapse supernovae is very similar to that of AICs (Fig. 4). However, because it takes more time after bounce for neutrino heating to drive an explosion in core-collapse supernovae, the time variation of the neutrino spectrum differs from core-collapse supernovae to AICs. Technically, one could differentiate core-collapse supernovae from AICs simply by this spectral resolution.

It is easier to differentiate core-collapse supernovae from AICs simply by their optical output. Supernovae are classified by their spectra (based on what lines are visible). The collapse of massive stars have spectra that match Type Ib, Ic, II supernovae, whereas AICs have spectra which are very similar to Type Ia supernovae.

We may also be able to distinguish rapidly rotating core-collapse supernovae from slowly rotating supernovae based simply upon their polarization. Using the first stellar models including rotating, Fryer & Heger (2000) found that rotation produced asymmetric supernova explosions, which may explain the polarization measurements of supernovae. This effect arises from the fact that the positive angular momentum gradient in the spinning core stabilizes against convection in the equator. Since convection is limited to the polar region, the supernova explosion is strongest there, and the resultant explosion is highly asymmetric (Fig. 5). It is currently believed that such asymmetries are necessary to produce the observed

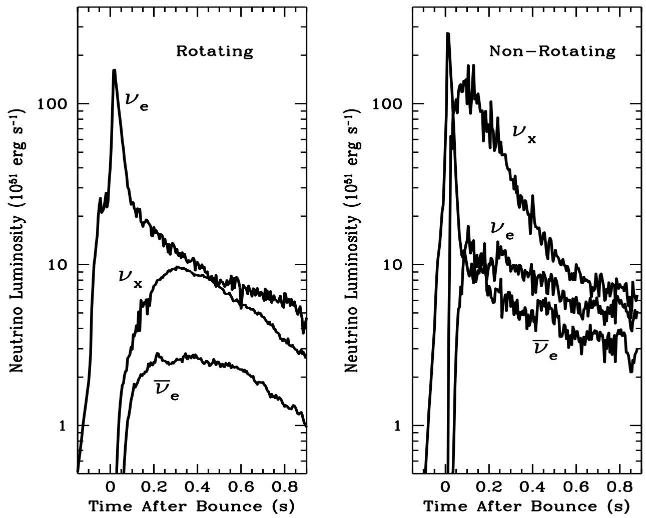

FIGURE 3. Neutrino luminosities versus time for a rotating and non-rotating progenitor. The non-rotating core has a much larger μ and τ (ν_x) neutrino luminosity, especially just after bounce. This is because the non-rotating core compresses more and, at the μ and τ neutrinosphere, the temperature is over a factor of 1.5 higher than that of the rotating core. Because of the large dependence of neutrino emission on temperature (the luminosity from pair annihilation $\propto T^9$), this small change in temperature has large effects on the neutrino luminosity.

polarization (Höflich 1991). With more accurate calculations and careful observations, we may be able to distinguish quickly and slowly rotating core-collapses.

Gravitational Wave Emission

In figure 1, we show the density profiles of 2 separate core-collapse simulations: one using the rotation profile calculated by Heger (1998), and the other using half that amount of angular momentum (see Fryer & Heger 2000 for details). The simulations by Heger assumed a near-maximally rotating main-sequence star and did not include any angular momentum transport caused by magnetic fields. Since this time, Heger has included a prescription for magnetic-field induced angular momentum transport, and the total angular momentum in the core has decreased somewhat. Note first that the lower angular momentum simulation is much denser than the full rotation simulation. Even though this simulation has less angular momentum (Fig. 2), its compactness leads to a proto-neutron star which is much more unstable (Fig. 3). In all cases, the angular momentum in these stars is initially much less than what is used in most GW core-collapse simulations, but as the strong polar explosion removes the matter along the poles (which had little angular momentum) the specific angular momentum of the remnant proto-neutron star can get very large. Unfortunately, at these times, the density is not high enough to produce very large GW signals from bar-modes and, if we are to detect GW emission from core-collapse, it will likely be from r-modes. In both cases, the resultant neutron star has millisecond spin periods, making these objects ideal r-mode candidates. At a rate up to 1 per 50 years in the Galaxy, r-mode driven GW emission from core-collapse supernovae remains a promising source of GW waves.

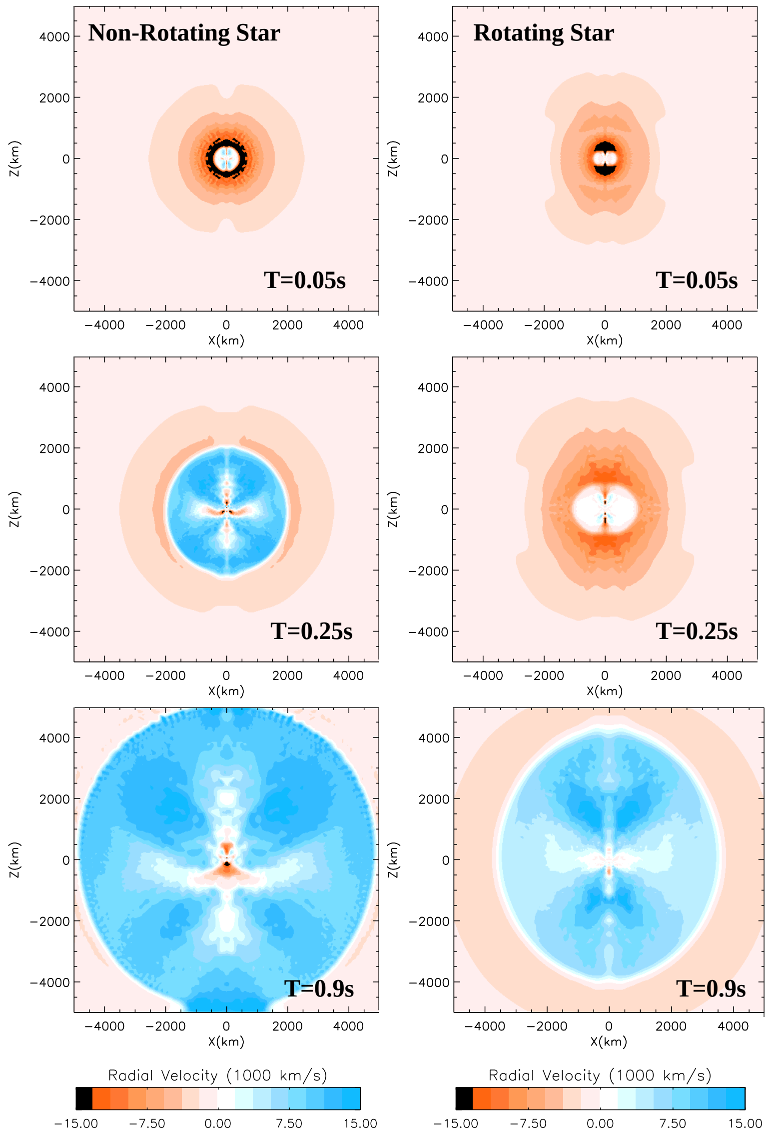

FIGURE 4. Radial velocity distribution of non-rotating and rotating models 0.05, 0.25, 0.5, and 0.9 s after bounce. At 0.9 s, the non-rotating model remains essentially spherical. The asymmetries in the velocities are caused by the buoyant convective bubbles which are driving the explosion. In contrast, the rotating model already shows strong asymmetries in the shock position and velocities.

COLLAPSE OF VERY MASSIVE STARS

As the mass of the collapsing star increases, the basic picture described above on core-collapse supernovae begins to change. Above 20-25 $M_{\odot}$, the supernova explosion is too weak to eject the entire star, and some of the star will fall back onto the neutron star 100-100,000 s after the supernova explosion (and after the GW emission). This fallback matter will push the remnant mass above the maximum neutron star mass, and it will collapse to form a black hole. Beyond $\sim$40-50 $M_{\odot}$, neutrino heating is unable to drive a supernova explosion and the star collapses to form a black hole. These direct-collapse stars will definitely have different GW emission than normal core-collapse simulations and also different optical output (they are known as "Collapsars" or "Hypernovae" and constitute one of the favored models for gamma-ray bursts). Unfortunately, beyond $\sim$40-50 $M_{\odot}$, mass-loss from stellar winds can dramatically change the mass of the star before collapse and it may be that nature does not produce any high-metallicity collapsar progenitors.

Stellar winds are driven by the opacity of metals in the stellar envelope. It is likely that as we reduce the fraction of metals in the star, mass-loss from winds will decrease. Population III stars are the first generation of stars formed in the early universe, when no metals existed (stars produce all of the metals we see today). In this section, we review the collapse of very massive, population III stars (100-500 $M_{\odot}$). If these stars are rotating, rotational (plus thermal) support prevents the star from immediately collapsing into a black hole. Just like core-collapse supernovae, rotating, very massive stars collapse and bounce, forming a proto-black hole (50-70 $M_{\odot}$within 1000-2000 km). This rotating proto-black hole is susceptible to bar instabilities and may produce a strong GW signal.

Formation Rate

Estimating an accurate rate of core-collapse from very massive stars depends on two major uncertainties: the fraction of stars which form with masses above 100 $M_{\odot}$and the number of these stars which actually collapse to form black holes. The mass distribution of stars at birth is known as the initial mass function (IMF). Today, the IMF is peaked toward low mass stars such that 90% of stellar core-collapse occurs in stars between 8 and $\sim$20 $M_{\odot}$and only 1% of core-collapse occurs in stars more massive than 40 $M_{\odot}$. However, recent simulations by Abel, Bryan, & Norman (2000) suggest that the typical mass of first generation stars may be peaked towards $\sim$ 100 $M_{\odot}$and it could be that a majority of Population III stars had masses in excess of 100 $M_{\odot}$.

The light from these very massive stars re-ionizes the early universe, and from this, we can derive a constraint on the formation rate of these stars. Although we expect that these photons ionized a significant fraction of the early universe, there should not be so many stars that they ionize the universe several times over. Using our best estimates of the re-ionization fraction, the amount of ultraviolet photons produced by these massive stars, and the ionization efficiency of massive stars, one estimates that roughly 0.01%-1% of the baryonic matter in the universe was incorporated into very massive stars. This calculation corresponds to roughly $10^4 - 10^7$ very massive stars produced in a $10^{11}\,M_\odot$galaxy, or a rate of massive stellar collapse as high as 1 every few thousand years! However, stars less massive than $\sim 260\,M_\odot$do not collapse, but explode in a giant thermonuclear explosion known as a pair-instability supernovae. Unfortunately, although we might believe our formation rate of very massive stars (within a few orders of magnitude), it is currently impossible to determine how many very massive stars are produced with masses beyond $\sim 260\,M_\odot$. The Galaxy could produce a million of these objects, or maybe just a few hundred. 1-10 million very massive stars is a secure upper limit.

Neutrino and Photon Outbursts

As a rotating massive star collapses, rotational support (plus thermal) support can actually halt the collapse and produce a weak bounce. What remains behind is a massive (but not dense in core-collapse standards) proto-black hole (Fig. 1). It takes a few seconds for neutrinos to cool this proto-black hole, allowing it to collapse to a black hole. The neutrino luminosity is nearly an order of magnitude higher than that of core-collapse supernovae (Fig. 6), but only lasts until the star collapses to form a black hole. When the star collapses, the μ and τ neutrino flux drops off first, and later, the electron neutrino flux. This occurs because the μ and τ neutrinos probe the interior of the proto-black hole, and as soon as an event horizon is formed, these neutrinos become trapped in the black hole. The electron neutrinos do not decrease significantly until the black hole expands enough to produce a cold accretion disk.

Fryer et al. (2001) have suggested that, if a magnetic jet mechanism works, the black hole accretion disk system produced during the collapse may produce a gamma-ray burst. The burst would likely have a longer duration than typical gamma-ray bursts and would, like the collapsar, be accompanied by a supernova-like explosion. Even if such a jet is not produced, the further accretion of material onto this black hole would produce an X-ray transient (at the Eddington flux) which would persist for about a day.

Gravitational Wave Emission

Although the density of the proto-black hole is much less than the density found in core-collapse supernovae (Fig. 2), the amount of mass in the proto black hole (up to $80\,M_\odot$) is nearly 70 times that of the proto-neutron star. The GW signal is very sensitive to the mass, and the collapse of these massive stars can produce very strong GW emission. The angular momentum in the the proto-black hole is high (Fig. 3) and these stars will certainly be unstable to secular instabilities and possibly dynamical bar-mode instabilities (Fig. 4). However, the temperature is too high to form r-mode instabilities. A final GW source could arise from ringing in the nascent black hole and we are actively studying its potential now.

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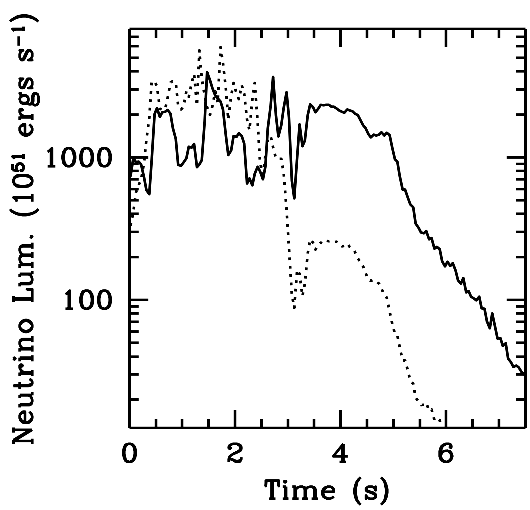

FIGURE 5. Neutrino Luminosity as a function of time from Model B. The μ and τ neutrinos (dotted line) dominate the neutrino emission until black hole formation. Shortly after the black hole forms, the event horizon grows beyond the μ and τ neutrinosphere (at 2.5 s) and drastically diminishes the neutrino luminosity. The electron neutrinos (solid line) do not decrease significantly until the black hole expands enough to produce a cool accretion disk.